A Multi-Sensors Wearable System for Remote Assessment of Physiotherapy Exercises during ACL Rehabilitation

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Abstract—**In this paper, the challenges associated with the design of a novel multi-sensor wearable system for the objective assessment of exercises during lower-limbs rehabilitation are described. The overall system architecture is defined, and finally both the implemented hardware and software platforms are illustrated in detail. Multiple sensing technologies are adopted including motion data, electromyography measurements, and muscle electro-stimulation. The software stack provides guidance to the users throughout the rehabilitation therapy sessions, and allows clinicians to access the data collected remotely in real-time thus supporting their clinical evaluation. Finally, preliminary results of the comparison between the knee joint angle estimated by the developed system against a gold-standard inertial-based system are provided showing promising results for future validation.**

Keywords — Sensors; ACL; IMU; EMG; Rehabilitation; Wearable.

I. INTRODUCTION

Over 200,000 anterior cruciate ligament (ACL) injuries occur in the USA alone annually, with more than half of these injuries requiring surgical reconstruction and subsequent rehabilitation [1]. The goal of the rehabilitation process is to return the patients to their pre-injury level, and the process typically involves the monitoring of the individuals' body motion when performing clinically defined tasks. While subjective evaluation by the clinician is still the main assessment occurring during sporadic medical examinations, additional quantitative monitoring tools have been developed [2]. Rating scales and questionnaires, such as KOOS, IKDC or WOMAC, are an example, but these tools are subjective and, even when utilized by experienced clinicians, may not be adequate or sensitive enough [3]. On the other side, marker-based or markerless camera-based motion analysis systems (e.g. Vicon) [4] represent the gold-standard technology adopted in gait analysis for quantitative movement analysis but their application is constrained by costs, access to specialist motion labs, as well as practicality of application for larger patient/subject groups.

The market for wearable sensors has been massively growing in the latest years and such technologies represent a viable alternative to gold-standard technologies able to guarantee remote real-time objective assessment in subjects involved in lower-limb rehabilitation owing to their small size and low-cost. Some examples of their use in biomechanics are shown in [5-6]. Those systems can establish a biofeedback loop with the patients using them, which empower the subjects and increase their compliance levels, typically defined as the weakest aspects in any rehabilitation regimen [7].

Many of the biofeedback systems incorporating wearable sensors described in the current literature rely on the adoption of motion sensors (e.g. accelerometers, gyroscopes) as the primary sensor modality used for data collection. Typical examples include the adoption of one or more sensors attached on the lower limbs with the aim to provide knee joint range of motion (ROM), gait variables, or some defined "quality of movement" measures during specific rehabilitation exercises [8-11].

Furthermore, wearable sensors providing physiological measurements, such as electromyography (EMG), are starting to gain researchers' attention owing to the possibility of acquiring insights on the neuromuscular system (i.e. muscle firing sequence, muscle activation) which are fundamental indicator used for clinical assessment and which provide a clear indication on the return to pre-injury levels [12]. However, only a limited number of studies so far have combined the adoption of motion sensors and EMG for an objective assessment [13-14], with only few dedicated to evaluate progress during a lower-limbs rehabilitation regimen [15].

Finally, electrical muscle stimulation (EMS) is an effective intervention typically adopted in rehabilitation for assisting motor functions [16]. Nevertheless, this technology has been rarely investigated in conjunction with wearable sensors in a rehabilitation context.

The present study described here investigates the possibility of developing a novel system which is wearable, unobtrusive, easy-to-use, wireless and able to transmit the data collected directly to a smartphone and a web server for a real-time knee assessment of the rehabilitation exercises by patients and clinicians. Multiple sensor technologies are integrated in the system with to goal to provide an end to end solution able to provide detailed and comprehensive knee-related biomechanics information and muscle activation/stimulation capabilities to clinicians and patients, and to enhance patients' motivation and engagement also increasing progress awareness. The manuscript is organized as follows. The system architecture is described in Section II, while Section III and IV describe the hardware platform

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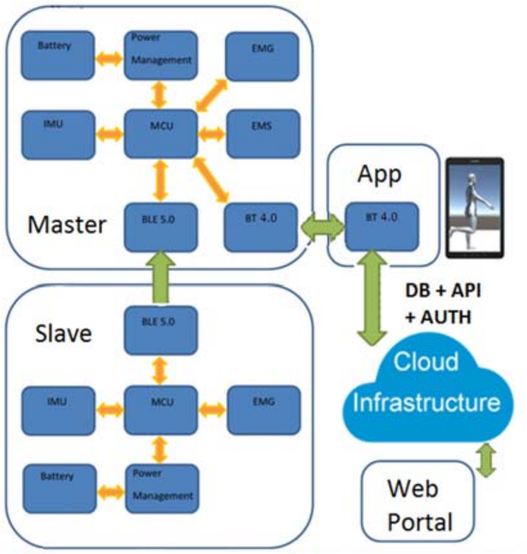

Fig. 1 System Architecture

and the software stack developed, respectively. Preliminary results and their discussion are in Section V.

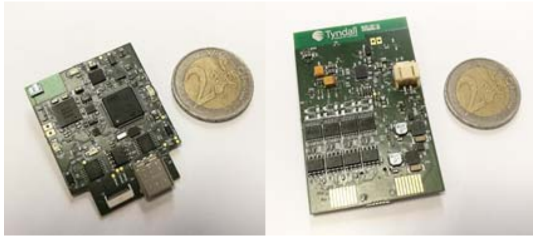

Fig. 2 PCB Platforms. Slave (left) and Master (right)

Fig. 3 Master sleeve electrodes and fabric

II. System Architecture

Figure 1 shows a block diagram of the overall system architecture. The system incorporates two inertial measurement units (IMUs) on the thigh and calf to fully account for all the joint degrees of freedom (DOF), EMG sensors located on relevant muscles on the lower limbs, and has the capability to electrically stimulate specific muscles heavily involved in the rehabilitation process.

The large amount of sensing data collected allows the system to provide an objective assessment of the exercise performance based on the comparison to standard patterns in healthy subjects, thus providing a clear picture of where the patient is in his/her rehabilitation process. The patients app allows the user to engage with the wearable device, retrieve useful information on the rehabilitation exercises, and have a guidance through the therapy sessions, with a humanoid replicating the movements of the patient in real-time during each exercise. Also, a score indicating the quality of the performance is shown at the end of each exercise, and the patient can go through the history of the exercises, thus being encouraged and motivated in reaching their goals. Clinicians can use a separate web portal to remotely monitor multiple patients' results on a dashboard, evaluate their progression in the rehabilitation, and standardize the therapy protocol for each subject on the basis of the collected results.

III. Hardware Platform

The hardware platform consists of two parts. One part is located on the thigh and the other one on the calf.

The device located on the calf (namely Slave) uses a subset of sensors, e.g. an IMU (9DOF) and the EMG sensors (4 electrodes) which monitor the gastrocnemius muscles (medial and lateral head). A detachable electronic board integrates the IMU, a Bluetooth 5.0 module for wireless communication to the Master unit (described below), a microcontroller, and battery management circuitry. The EMG sensors are fully embedded into a sleeve type textile. The wiring of the electrodes to the electronic board consists of wires connected to the electrodes with conductive epoxy.

The device located on the thigh (namely Master) is responsible for the communication with the Slave unit and the user interface on the smartphone. Again, a second detachable electronic module integrates the IMU, a Bluetooth 5.0 module for fast communication with the Slave unit, microcontroller, battery management, and a second wireless module (Bluetooth 4.0) for communication with the mobile device. Also two EMS circuits and four EMG sensors are included. Both EMS and EMG use conductive textile (gold plated) that is biologically compatible with the human skin to make contact with the required muscle groups. More precisely the EMS circuits stimulate the quadriceps and the hamstrings (front and back of the thigh) and, to obtain the best results, 4 electrodes are used. Regarding the EMG sensors, 8 electrodes are required to measure the signals generated by muscles of interest (e.g. rectus femoris, vastus lateralis, semitendineous, and biceps femoris) indicated by clinical recommendations. Surface EMG have been adopted for both units adopting a passive dry electrode solution. Likewise, dry electrodes are adopted for EMS. Conductive non-stretchable textile for the EMG and EMS electrodes was used for initial prototyping, while standard lycra shorts without padding and elastic textile were used as a support for the master and slave units, respectively. Sensor placement was firstly defined on a user's leg and then transferred on a mask which was then used as a reference to cut the non-stretchable textile which was put in the defined place via textile glue. Conductive epoxy and flexible wires (standard multi-strand wires) were finally adopted to route the signals to the PCB electronic boards. To improve the contact between the electrodes and skin, spongy non-conductive material was glued on top of the electrodes. The overall system was finally covered with one layer of non-stretchable textile for additional protection.Figure 2 shows the PCB electronic boards developed for the Master and Slave units, while Figure 3 illustrates the sleeve textile built for accommodating all the sensing technologies on the Master unit. The PCB boards are enclosed in two custom designed 3D-printed enclosures attached to the textile via a snap-fit mechanism to facilitate the detachment from the sleeves for recharging. The size of the Master PCB board with enclosure is 90 x 60 mm, while for the Slave PCB is 70 x 80 mm. Both units rely on 32-bits microcontroller with built-in floating point units with up to 1 Mb Flash memory and 196 Kb of RAM. While the power consumption in sleep mode for both units is 25 uA, it reaches 300 mA for the Master board and 42 mA for the Slave board (at 100% duty cycle). The Master device additionally includes haptic feedback [17] which could be adopted for a real-time biofeedback to the user or for gamification purposes, and a microSD card for data storage.

IV. Software Stack and System Operation

The software stack implemented consists of three parts. The first part aims to interface the hardware platform with the mobile application. The Slave unit wirelessly streams the data collected (IMU and EMG measurements from 2 muscles) to the Master unit. In turn, the Master unit collects the data received from the Slave and synchronizes them with the data monitored by the sensors located on the thigh (IMU and EMG measurements from 4 muscles) forming a single packet. A fully embedded sensor fusion algorithm, e.g. [18], is implemented on-board to define the 3D orientation (as quaternions) of the two limbs. These quaternions are appended in the data packet defined by the Master unit and transmitted wirelessly to the smartphone app. The Master unit can also accept incoming data packets from the mobile application to activate and configure haptic feedback and muscle electro-stimulation.

The second part of the stack involves the implementation of the mobile application designed to work for Android smartphones. The application is divided in 4 sections: *Home, Knowledge Base, My Self-Care Plan,* and *Recovery Tracker*.

The *Home* section displays basic information about the mobile app, while the *Knowledge Base* section provides a list of FAQs related to the recovery process. The *My Self-Care Plan* section contains an exercise-based rehabilitation program divided in 5 stages (from pre-surgery to return-to-sport). This program has been defined according to clinically available recommendations and there are no timelines associated, as progressing from one stage to the following one depends on the user's results. The *My Self-Care Plan* shows the stages with the related list of exercises, however the user can perform only the exercises which belong to the stage he/she is currently associated. Once tapping on an exercise, a new screen shows the key details on how to perform it correctly before directing the user to an additional screen where a 3D human body (implemented in Unity 3D) reproduces the movements of the user's lower limbs along the sagittal plane based on the 3D orientation information provided by the hardware platform. Additional analytics is performed on-board the mobile device involving repetition segmentation and counting [8] as well as a possible evaluation of the "quality of movement" or score of the repetitions/exercises based on the knee trajectory compared

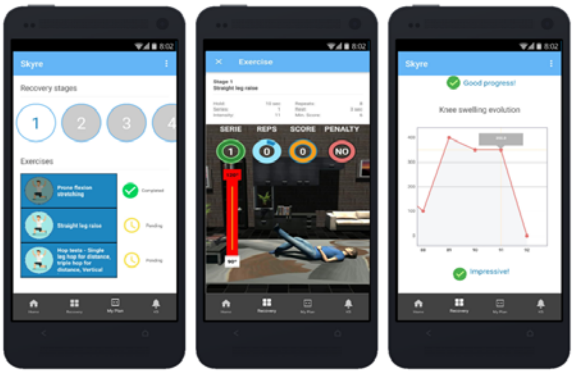

Fig. 4 Mobile application: My Self-Care Plan (left), 3D human body performing exercise (centre), and Recovery Tracker (right)

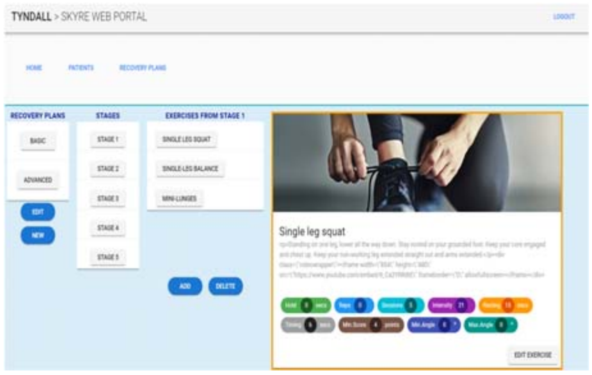

Fig. 5 Web portal. Recover Plans tab

against healthy control [19]. Results associated to the exercise performance are shown to the user at the end of the exercise, and the user can manually input indications on pain and effort experienced during the test. All the collated results are then available in the *Recovery Tracker* section designed to record patient's recovery progress over the rehabilitation process showing both objective and subjective outcomes. Visual graphs and representations are used to support the patient in interpreting the feedback. The IKDC questionnaire [20] is also implemented in this section and can be completed by the user periodically. Finally, the collected results for each patient can be moved wirelessly to a database available on cloud server via an implemented RESTful API. To guarantee the data security, the cloud server is managed through a virtual machine provided by a regulatory compliant cloud hosting provider based in Ireland. The data in the database can be retrieved via a web portal which allows clinicians to access remotely the data obtained by the hardware platform.

This web portal represents the third component of the software stack and includes authentication methods, a Patient tab showing information on the patient (e.g. recovery stage, analytics) and is responsible for the management of the users' profiles, and a Recovery Plans Tab for giving the clinician the possibility to manage and customize the rehabilitation program for each user. The authentication methods involve mechanisms implemented into the API to authenticate a clinician into the platform by validating the login credentials against pre-registered users into the database. Sensitive data in the cloud infrastructure is encrypted (via Advanced Encryption Standard - AES) for increased security. Figures 4-

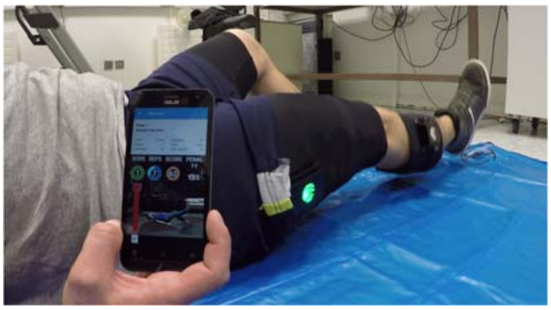

Fig. 6 Fully working system

5 depicts a selection screens on the mobile applications, and a section on the web portal, respectively.

V. Preliminary Results and Discussion

This paper describes the development of a novel wearable unobtrusive system for remote real-time objective assessment of physical exercises throughout a rehabilitation protocol. Both hardware and software platforms defining the system have been described including the hardware architecture, sensing technologies adopted, prototyping process, mobile application and web portal implementation, as well as wireless communication among all the system components. Sensing include motion data, EMG measurements, and the possibility to adopt muscle electro-stimulation. An example of the fully working system is shown in Figure 6. The overall system has a throughput of 30 Hz (considering all the sensing data), and the wireless range between the hardware platform and the mobile device is > 20 m, suitable for typical indoor environments. The overall power consumption of the platform guarantees a minimum of 2 hours of operation when using a standard Li-Ion battery with 1200 mAh capacity. The knee flexion-extension angle obtained by the developed system was compared for different tasks against the XSens (Xsens MTw AWINDA and Xsens MVN Studio, Xsens Technologies BV [21]) as a gold-standard. Eleven healthy subjects were tested, and each subject performed all the exercises (ten repetitions per exercise). Root mean square error (RMSE) and Pearson's coefficient were calculated for each subject/exercise and the average results are reported in Table I. Seven data collections out of 55 with errors in terms of data loss or synchronization were discarded. The RMSE was between 5.5 and 10.4 deg for all the exercises, thus showing a good accuracy. Pearson's r was excellent (> 0.9) in 4 out of 5 exercises, while in one it showed moderate agreement.

The large amount of data collected can support clinicians in their evaluation of patients involved in ACL rehabilitation. Moreover, the developed mobile application can provide guidance to the users through the rehabilitation therapy sessions, thus increasing awareness and improving compliance. The data analytics aspects can be further improved by including additional metrics for both patients and clinicians (i.e. muscle fatigue during exercises, strength, stability). Further test are currently ongoing for the development of a system more robust, durable, and washable. Future works will also consider usability studies with potential end-users to further investigate the impact of the overall system and support future developments.

TABLE I. Knee Joint Angle Accuracy Estimation

Exercises	*Hamstring Curl*	*Mini Lunges*	*Single Leg Squat*	*Straight Leg Raise*	*One Leg Deadlift*
RMSE (SD) - deg	10.4 (3.8)	6.4 (5.6)	7.6 (4.55)	5.5 (3.8)	8.2 (6.1)
r (SD)	0.99 (0.005)	0.99 (0.004)	0.99 (0.003)	0.63 (0.19)	0. 92 (0.05)

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